



NRL/MR/6180--04-8734

An Analysis of the Potential Advantages of Discharging Water Mist in the Primary Damage Area Immediately Following a Weapon Hit

GERARD G. BACK, III

JOSEPH L. SCHEFFEY

Hughes Associates, Inc.
Baltimore, MD

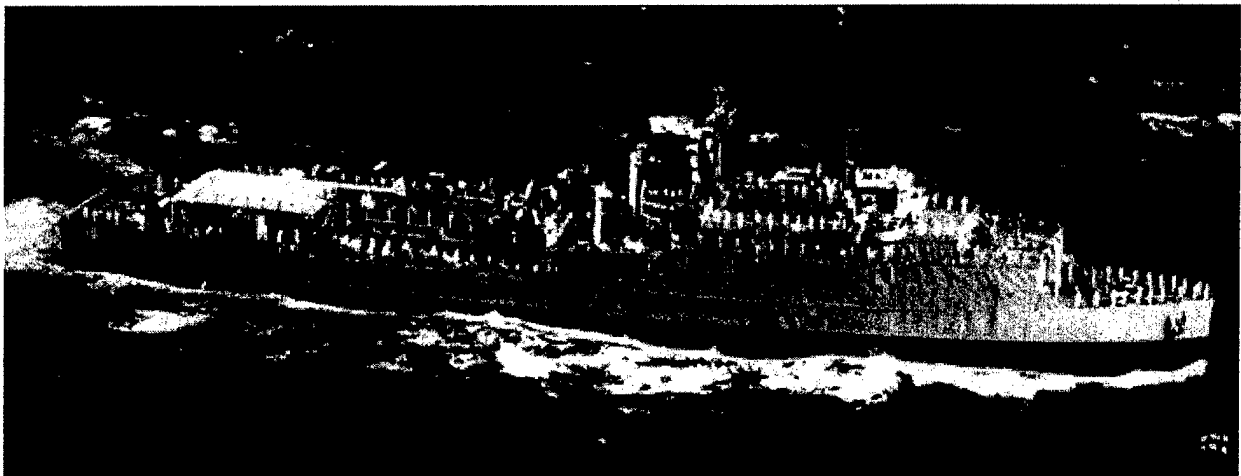
FREDERICK W. WILLIAMS

JOHN P. FARLEY

Navy Technology Center for Safety and Survivability
Chemistry Division

January 12, 2004

20040219 212



Approved for public release; distribution is unlimited.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) January 12, 2004		2. REPORT TYPE Memorandum Report		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE An Analysis of the Potential Advantages of Discharging Water Mist in the Primary Damage Area Immediately Following a Weapon Hit				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Gerard G. Back, III,* Joseph L. Scheffey,* Frederick W. Williams, and John P. Farley				5d. PROJECT NUMBER 61-7878-A-3-5	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Research Laboratory, Code 6180 4555 Overlook Avenue, SW Washington, DC 20375-5320				8. PERFORMING ORGANIZATION REPORT NUMBER NRL/MR/6180--04-8734	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Naval Sea Systems Command 1333 Isaac Hull Avenue, SE Washington Navy Yard, DC 20376				10. SPONSOR / MONITOR'S ACRONYM(S)	
				11. SPONSOR / MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES *Hughes Associates, Inc., Baltimore, MD					
14. ABSTRACT A water mist system that incorporates a survivable design has the potential to significantly reduce the thermal conditions in the primary damage area (PDA) following a weapon hit. This reduction in thermal conditions would certainly prevent flashover and could potentially prevent fire spread to adjacent compartments. The analysis put forth in this paper demonstrates that the likelihood of the PDA to reach flashover following a weapon hit is a function of the size of the opening to the weather created by the blast. Up to the point where the fire becomes fuel surface limited, the larger the vent opening, the greater the fire size and the higher the resulting compartment temperatures. The increased air flow provided by the larger vent opening also dictates the amount of water vapor required to saturate the gases in the PDA. As a result, the amount of mist required to achieve thermal management is also a function of the size of the vent opening. The results of this analysis demonstrate that the conditions produced by the fire following a typical weapon hit could be mitigated by appropriately discharging a minimal amount of water mist into the PDA.					
15. SUBJECT TERMS Water mist; Fire suppression; Fire					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES 27	19a. NAME OF RESPONSIBLE PERSON Frederick W. Williams
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code) 202-767-2476

CONTENTS

1.0	INTRODUCTION.....	1
2.0	OBJECTIVE	2
3.0	TERMINOLOGY.....	3
4.0	TECHNICAL DISCUSSION.....	4
4.1	Analytical Techniques.....	4
4.2	Application/Results.....	8
4.2.1	Defining The Compartment Geometry	8
4.2.2	Defining the Compartment Ventilation.....	9
4.2.3	Defining The Water Mist System Parameters.....	9
4.2.4	Analytical Assessment/Trends	9
4.2.4.1	Two-layer Analysis.....	11
4.2.4.2	One-layer (well-stirred) Analysis	13
4.2.4.3	Analytical Summary	16
5.0	WATER MIST SYSTEM DESIGN CONSIDERATION	20
6.0	SUMMARY	21
7.0	REFERENCES.....	21

LIST OF ACRONYMS

APDA	Adjacent to Primary Damage Area
CFAST	Consolidated Fire and Smoke Transfer
DC	Damage Control
DCA	Damage Control Assistant
DC-ARM	Damage Control – Automation for Reduced Manning
IMO	International Maritime Organization
NRL	Naval Research Laboratory
NSWC	Naval Surface Warfare Center
PDA	Primary Damage Area
SCS	Supervisory Control System
SES	Smoke Ejection System
SVM	Ship Vulnerability Model
VAR	Vulnerability Assessment Report
WET	Weapons Effects Test

AN ANALYSIS OF THE POTENTIAL ADVANTAGES OF DISCHARGING WATER MIST IN THE PRIMARY DAMAGE AREA IMMEDIATELY FOLLOWING A WEAPON HIT

1.0 INTRODUCTION

The recently completed Damage Control – Automation for Reduced Manning (DC-ARM) program helped to identify and develop the systems, equipment and techniques that will be required to significantly reduce the manning requirements for damage control (DC) and improve DC performance. The DC-ARM technologies identified to contribute most to improved DC performance and reduced manning included:

- Water mist for fire suppression and fire containment,
- Sensors for fire detection and fire characterization,
- Fire main distributive controls for robustness, survivability and isolation of fire main ruptures,
- Smoke ejection system (SES) for clearing smoke on the DC deck,
- Access closure monitoring to improve situation awareness,
- Video installed in most spaces for compartment monitoring and reduce investigation workload, and
- Supervisory Control System (SCS) to enable effective situation awareness and overall control of the DC response.

The DC-ARM program was built upon a series real-scale technology demonstrations that progressed from manual (FY 98) [1], to remote manual (FY 00) [2], to automated (reflexive) control in FY 01 [3] for the DC response. The program demonstrated that the DC manpower requirements on a modern destroyer-type ship could be significantly reduced from present manning level of 105 to 45 people, with the proper integration of DC system automation and improved DC doctrine (organization & procedures).

Manuscript approved August 19, 2003.

One important finding identified during the DC-ARM program [2,3] was the requirement to reduce the thermal threat in the primary damage area (PDA) to complete the recovery actions in the adjacent primary damage area (APDA) spaces. During the DC-ARM program, this was accomplished through manual fire fighting using an indirect attack. The reduction in the thermal conditions in the PDA (and reduced likelihood for fire spread) observed during these tests created and generated the interest of using a survivable water mist system to achieve similar results.

The current DC-ARM water mist system installed on the ex-USS *Shadwell* was designed to meet the fire hazard management objectives established by the International Maritime Organization (IMO) fire test protocols for "accommodation, public spaces and service areas" on civilian ships [4]. The IMO terminology for "Accommodation spaces, Corridors, Public spaces and Service areas" corresponds in Navy terminology to "Small spaces, Passageways, Large spaces and Storage areas," respectively. The system consists of uniformly spaced overhead open pendent nozzles. The nozzles have a k-factor of 1.9 Lpm/bar^{1/2} (0.13 gpm/psi^{1/2}) and are installed with a maximum nozzle spacing of 3.5 m (11.5 ft). The system is designed to operate at 70 bar (1000 psi) and to discharge 0.4 Lpm/m³ (0.003 gpm/ft³), the value currently used for the LPD-17 machinery spaces [5].

Since the system is designed to commercial standards, it is unlikely to survive in the primary damage area (PDA). Previous battle damage reports have shown that systems running through the space, particularly in the overhead near the centerline of the ship, are most susceptible to damage and are unlikely to survive the blast. As a result, the current system is likely to be limited in its ability to prevent flashover in the PDA. To achieve automated flashover suppression in the PDA, more survivable water mist system designs need to be developed and tested. Two such designs containing sidewall nozzles have already been identified [6,7].

Prior to investigating more survivable design/approaches, the amount of water required to control the fire in the PDA and prevent fire spread to adjacent spaces needed to be identified. This paper analyzes the effects of discharging mist into the PDA and its ability to thermally manage the conditions in the space. The analysis was then applied to a range of battle damage conditions to demonstrate the potential advantages of this approach.

2.0 OBJECTIVE

The objective of this analysis was to identify the potential advantages (thermal management capabilities) of spraying water mist into the PDA immediately following a weapon hit. Analytical techniques, incident data and previous experimental results were analyzed and combined to form the basis of this investigation.

3.0 TERMINOLOGY

The following terms should be understood prior to further discussion.

1. **Primary Damage Area (PDA)** – These compartments are directly affected by the weapons blast. The bulkheads, decks or overheads within these compartments are either fragmented or removed as result of the overpressure. It is assumed that there is free communication between all areas of the PDA.
2. **Adjacent to Primary Damage area (APDA)** – These compartments/spaces border the PDA. They share a common boundary (i.e., bulkhead, overhead, or deck) with a compartment that is part of the PDA. There is no free communication between the PDA and APDA. Combustibles in these compartments have the potential to ignite due to heat transferred through the boundary from the PDA.
3. **Control** – To limit the fire growth rate/heat release rate of the fire and to minimize the likelihood of fire spread to an adjacent space.
4. **Suppression** – A significant reduction in fire size (heat release rate) to a minimal value.
5. **Extinguishment** – A reduction of the fire size (heat release rate) to the point where flaming combustion ceases to exist.
6. **Flashover** – The transition from a localized fire to a fully developed fire where all fuel surfaces are burning and the compartment fills with flame. This condition has been linked empirically to upper layer compartment temperatures on the order of 500-600 °C (923-1112 °F) [8].
7. **Tenable Conditions** – Based on the effects that elevated temperatures have on humans and electronic equipment, a maximum temperature of 80 °C (175 °F) is considered tenable [2]. In making this determination, it was assumed that response team members would be outfitted in coveralls, flash gear, and breathing masks, such that no skin would be exposed.
8. **Setting Boundaries** – Maintaining tenable conditions and preventing a fire from becoming established in APDA compartments.

9. Piloted Ignition – Flaming combustion is initiated by an external (small) source, such as a spark or a small independent flame. Conditions required for piloted ignition consist of a minimum heat flux of 10 kW/m^2 [9] and/or fuel surface temperature between $200\text{-}300^\circ\text{C}$ ($392\text{-}572^\circ\text{F}$) [10].
10. Spontaneous Ignition – Flaming combustion is initiated by heating from an external source in the absence of a pilot. Conditions required for spontaneous ignition consist of a minimum heat flux of 20 kW/m^2 [9] and/or fuel surfaces temperature between $250\text{-}450^\circ\text{C}$ ($482\text{-}842^\circ\text{F}$) [10].
11. Fuel Limited Fire – A fire where the heat release rate is controlled by the combustible materials (i.e., quantity, burning characteristics, and surface area) in the compartment [10].
12. Ventilation Limited Fire – A fire where the heat release rate is controlled by the air flow into the compartment (both natural and forced) [10].
13. Ventilation Factor – $A\sqrt{H}$, where A is the area of the vent opening in square meters and H is the height of the vent opening in meters. This parameter defines the maximum air flow into a compartment during a ventilation limited fire and has the units of $\text{m}^{5/2}$ [10].
14. Thermal Management – The ability of a water mist/spray system to maintain the temperatures in a compartment to acceptable levels. (Acceptable levels may be based on either flashover suppression, fire spread, or tenability.)

4.0 TECHNICAL DISCUSSION

4.1 Analytical Techniques

During a typical weapon hit, the short duration high intensity thermal pulse created by the detonation of the warhead is followed shortly thereafter by a fully developed compartment fire. The initial temperature spike caused by the detonation and consumption of the residual missile fuel/propellant cannot easily be mitigated by the surviving portion of the mist system. Separate R&D programs have been proposed to study the effects of preemptive discharge of water mist on mitigating the effects of the blast. It is generally believed that the duration of this spike is too short to cause fire spread to adjacent spaces through intact boundaries. As a result, the objective of the mist system should be to mitigate the effects of the ensuing compartment fire, which is the focus of this investigation [11].

Thermally managing the conditions in the PDA during the ensuing compartment fire has two significant effects on the conditions in the space. First, the reduction in temperature will decrease the air flow rate into the compartment, which lowers the maximum fire size that can be supported by any natural vent openings. Second, if the water mist system can create adequate turbulence in the region around the fire, the water vapor/steam and vitiated gases will dilute the oxygen, hence reducing the fire size even further. In either case, the first step in the analysis is to predict the temperatures in the PDA. These temperatures were predicted by conducting an energy balance calculation on the compartment (PDA) expressed by the following equation:

$$\dot{Q}_{Fire} = \dot{Q}_{Boundary} + \dot{Q}_{Vent} + \dot{Q}_{Water} \quad (1)$$

where \dot{Q}_{Fire} is the heat release rate of the fire; $\dot{Q}_{Boundary}$ is the energy lost through the walls, ceiling, and floor; \dot{Q}_{Vent} is the energy lost out of the vent opening; and \dot{Q}_{Water} is the energy absorbed by the mist.

The following assumptions were made to simplify the calculation:

- (1) Combustion was complete and takes place entirely within the confines of the compartment (the heat release rate of the fire is a constant);
- (2) The temperature was uniform within the compartment at all times (after discharge), and the gases exhausted were assumed to be at the compartment temperature;
- (3) The exhaust gases and the gases contained in the compartment were assumed to be saturated with water vapor;
- (4) A single surface heat transfer coefficient was used for the entire inner surface of the compartment;
- (5) The heat transfer through the compartment boundaries was unidimensional, i.e., corners and edges are ignored and the boundaries are assumed to be "infinite slabs;" and
- (6) Mist droplets were assumed to be heated to the compartment gas temperature.

The individual components of Equation (1) were calculated as follows: assuming a ventilation limited fire, the heat release rate is calculated using the following equations:

$$\dot{Q}_{Fire} = C \dot{m}_{air} \Delta H_{R_{Air}} \quad (2)$$

where C is the combustion efficiency, \dot{m}_{air} is the air/oxygen available to support combustion, and $\Delta H_{R_{Air}}$ is the heat of reaction of air.

The energy/enthalpy lost through the boundaries of the compartment can be estimated using an overall heat loss coefficient and the following equation:

$$\dot{Q}_{Boundary} = h_T A_S \Delta T \quad (3)$$

where h_T is an overall heat transfer coefficient (30 W/m²K was used based on previous measurements [12], A_S is the area of the walls and ceiling of the compartment (m²), and ΔT is the temperature difference between the steady-state compartment temperatures and the initial ambient conditions.

The energy/enthalpy lost out of the vent opening is comprised of two components: the energy required to heat the air to the compartment temperature, and the energy associated with the saturated water vapor leaving the compartment. The radiative losses out of the vent opening were assumed to be negligible. The vent losses are given by the following equation:

$$\dot{Q}_{Vent} = \dot{Q}_{gas} + \dot{Q}_{H_2O_{vapor}} \quad (4)$$

The losses associated with heating the air to the compartment temperature are given by the following equations:

$$\dot{Q}_{gas} = \dot{m}_{gas} C_p \Delta T \quad (5)$$

where \dot{m}_{gas} is the mass flow rate of fire gases out of the compartment, C_p is the specific heat of the gas, and ΔT is the temperature difference between the steady-state compartment temperatures and the ambient air entering the compartment. If we assume $\dot{m}_{air} \approx \dot{m}_{gas}$ (i.e., ignore the increase in mass flow rate resulting from the fuel and water), then the mass flow rate through the compartment can be estimated using Equation (6), which is applicable to well-stirred compartments [10].

$$\dot{m}_{air} = \frac{2}{3} A H^{1/2} C_d \rho_0 (2g)^{1/2} \left(\frac{(\rho_0 - \rho_F) / \rho_0}{\left[1 + (\rho_0 / \rho_F)^{1/3} \right]^3} \right)^{1/2} \quad (6)$$

where A is the area of the vent opening, H is the height of the vent opening, ρ_0 is the density of air at ambient temperature, ρ_F is the density of the gases inside the compartment, $C_d = 0.7$ and $g = 9.81 \text{ m/s}^2$. The density of gases is a function of temperature and must be calculated simultaneously with the compartment temperature. If we assume the air entering the compartment is dry (no water vapor content) and leaves as saturated vapor, the losses associated with this vapor can be determined by the following equations:

$$\dot{Q}_{H_2O_{\text{vapor}}} = \dot{m}_{\text{air}} \gamma_{H_2O_{\text{vapor}}} L_v \quad (7)$$

where \dot{m}_{air} air was calculated using Equation (6), L_v is the heat of vaporization of water, and $\gamma_{H_2O_{\text{vapor}}}$ is the mass fraction of water vapor in the gases leaving the compartment. The mass fraction can be calculated using Dalton's Law if we know the partial pressure of the water vapor and assume it behaves as an ideal gas. The partial pressure of the water vapor is given by the following equation [13]:

$$P_v = e^{(18.3 - (3816.44/(T - 46.13)))} \quad (8)$$

where P_v is the partial pressure of the water vapor in mm Hg (torr), and T is the temperature of the gas in degrees Kelvin.

The mass fraction of the water vapor was then determined using the following equation:

$$\gamma_{H_2O_{\text{vapor}}} = \frac{\left(\frac{P_v}{P}\right) M_{W_{H_2O}}}{\left(\frac{P_v}{P}\right) M_{W_{H_2O}} + \left(1 - \frac{P_v}{P}\right) M_{W_{\text{Air}}}} \quad (9)$$

where P is the pressure of the gas (in this case atmospheric pressure (760 mm Hg)), and $M_{W_{H_2O}}$ and $M_{W_{\text{Air}}}$ are the molecular weights of the water vapor and air, respectively.

Notice that the energy/enthalpy loss associated with the water vapor does not include the heat required to heat the water to the estimated temperature. This was included in the term associated with the water losses.

The energy absorbed by the water mist is determined by the following equation:

$$\dot{Q}_{\text{water}} = \dot{m}_{\text{water}} C_p \Delta T \quad (10)$$

where \dot{m}_{water} is the mass flow rate of the water mist system, C_p is the specific heat of water, and ΔT is the temperature difference between the ambient and heated water based on the initial assumptions.

Once the size, compartment parameters, and water flow rate were known, the steady-state oxygen concentration was calculated by first determining the amount of oxygen consumed by the fire and then diluting the oxygen with saturated vapor. The amount oxygen consumed by the fire was calculated using the following equation:

$$\dot{Q}_{Fire} = \dot{m}_{air} \Delta H_{R,O_2} (\gamma_{O_2,amb} - \gamma_{O_2,dry}) \quad (11)$$

where \dot{Q}_{Fire} is the heat release rate of the fire, \dot{m}_{air} is the mass flow rate of air into the compartment using Equation (6), $\Delta H_{R,O_2}$ is the heat of reaction oxygen, and the gammas are the mass fractions of oxygen in the air flow into $(\gamma_{O_2,amb})$ and out of $(\gamma_{O_2,dry})$ the compartment. The mass fraction of oxygen calculated by Equation (11) was then saturated with water vapor using the following equation:

$$\gamma_{O_2,ss} = \gamma_{O_2,dry} (1 - \gamma_{H_2O,vapor}) \quad (12)$$

These steady-state oxygen concentrations were used to govern the heat release rate of the fire depending on the approach taken in the analysis and the conditions in the PDA.

4.2 Application/Results

4.2.1 Defining The Compartment Geometry

There is a reasonable degree of consistency between the damage predicted by the Ship Vulnerability Model (SVM) developed by the Naval Surface Warfare Center, Carderock Division (NSWC/CD) [14] and that observed during actual weapon hits. The SVM has been used during numerous vulnerability assessments (VARs) to predict the damage for a limited number of ship types and a range of attack weapons. The results suggest that the damage produced by the detonation of a medium sized weapon is typically two to three decks high, approximately 30 m (100 ft) long and spans the width of the ship. As a result, a compartment 30 m (100 ft) long, 10 m (33 ft) wide, and 5 m (16 ft) high was selected as the basis for this analysis.

4.2.2 *Defining the Compartment Ventilation*

In a previous study, the Naval Research Laboratory (NRL) has bounded the likelihood (and time) for compartments subjected to weapons induced damage to reach flashover [15]. The analysis was conducted for steel compartments with natural ventilation (openings to the weather). Twenty-seven compartment/vent configurations were analyzed using the multi-zone computer model, "Consolidated Fire and Smoke Transfer," CFAST [16]. The results show that the likelihood of a compartment to reach flashover is a function of the ventilation factor to compartment surface area ratio. The ventilation factor, $A\sqrt{H}$ (where A is the area of the vent (m^2) and H is the height of the vent (m)), defines the maximum heat release rate in the compartment and the energy losses out of the vent openings. The energy losses through the boundaries are a function of the compartment surface area (A_s) defined as the area of the walls and the ceiling and excludes the floor or the vent area. The results suggest that only compartments with ventilation factor to surface area ratios greater than $0.015 m^{5/2}$ are likely to produce and sustain flashover conditions (Figure 1). For extremely large vent openings, the fires become fuel limited, and the severity of the fire is decreased. As a result, ventilation factors up to $25 m^{5/2}$ were included in this evaluation. A ventilation factor of $25 m^{5/2}$ corresponds to an opening one deck high (2.4 m (8 ft)) and 6.7 m (22 ft) long. Forced ventilation was not considered in this analysis.

4.2.3 *Defining The Water Mist System Parameters*

Since the water mist system design for the DC-ARM program is being refined, and due to the fact that the conditions of the system would be unknown after the weapon hit, a range of water mist discharge rates were included in this evaluation. The maximum discharge rate analyzed is 40 to 50 percent of the current design condition. During the analysis, it was assumed that the mist is used at 100 percent efficiency. In an actual design and/or specific evaluation, the inefficiencies associated with the spray characteristics of the system and the conditions in the PDA (i.e., clutter and obstructions) would need to be considered. A discussion of potential system designs including survivability issues is provided later in this report.

4.2.4 *Analytical Assessment/Trends*

The primary unknown in this assessment is whether the space will become well-stirred (i.e., a single homogeneous layer) during the mist discharge. The conditions (i.e., size, shape, and degree of obstructions) in the PDA and the characteristics of the water mist system (i.e., flow rate, drop size, and spray momentum) will govern this phenomenon.

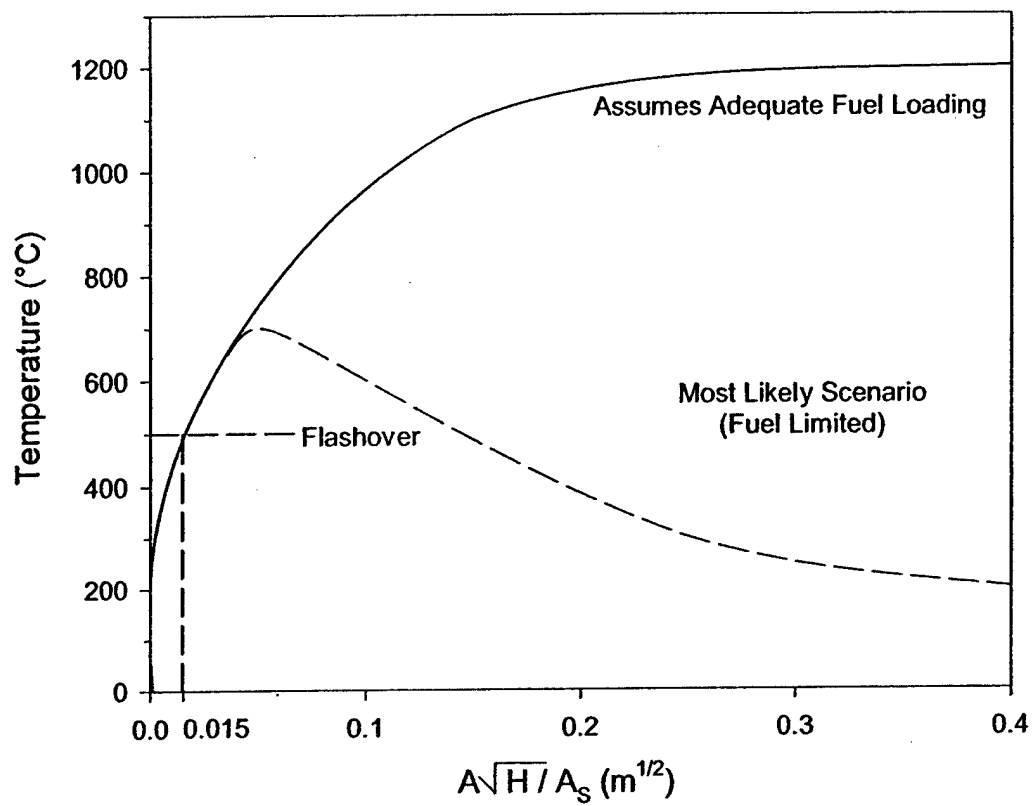


Figure 1 – Conditions Required to Flashover the PDA

In an attempt to bound the potential conditions in the space, two analytical approaches were used in this analysis. The first approach allowed the fire to grow until all of the air/oxygen entering the vent opening was consumed by the fire. These conditions would potentially occur if the PDA was not well-stirred (i.e., a two-layer system with a hot upper layer and a cold lower layer) and the fuel was located low in the space. Alternatively, these conditions could also be produced if the burning takes place primarily near the vent opening well away from the mist nozzles. The second approach assumed that the space became well-stirred, resulting in superior thermal management capabilities to the previous approach. The reason being that the heat release rate of the fire was regulated by the oxygen concentration in the compartment. The heat release rate was held constant once the oxygen concentration in the space dropped to 13 percent (the limiting oxygen concentration for most fuels [17]).

4.2.4.1 Two-layer Analysis

When the conditions in the PDA are not well-stirred and/or the burning occurs close to the vent opening, the water vapor/steam and vitiated gases contained in the space may not affect the burning characteristics of the fire. In this scenario, almost all of the oxygen entering the PDA would be consumed by the fire. In other words, the efficiency factor (C) in Equation (2) becomes one.

The analysis balance was conducted for a range of water mist discharge rates (0-5 kg/s (0-80 gpm)) and ventilation factors (0-25 $\text{m}^{5/2}$) on the 1500 m^3 (54,120 ft^3) compartment described previously. The steady-state temperatures predicted in the PDA as a function of water mist discharge rate and ventilation factor are shown in Figure 2. As shown in this figure, vent factors larger than 10 $\text{m}^{5/2}$ are adequate to flashover the PDA in the absence of water mist.

For smaller vent openings (smaller vent factors), when the mist discharge rate is greater than the evaporation rate, the temperatures are reduced below 100°C with only minor differences in temperature for variation in mist discharge rate (2°C/(kg/s)). For the larger vent openings when all of the mist is evaporated, the reduction in compartment temperature is linear as a function of mist discharge rate. The results show that the temperature is reduced 100°C per kg/sec of mist discharge. Based on these results, it can be concluded that in order to thermally manage the conditions in the space to temperatures less than 100°C for the range of vent factors included in this analysis, the mist discharge rate must be greater than 0.5 (kg/s)/ $\text{m}^{5/2}$. It should be noted that this relationship is not perfectly linear and that the critical value of 0.5 (kg/s)/ $\text{m}^{5/2}$ applies to the larger ventilation factors. The critical value for the smaller vent factors can be slightly reduced as the ventilation factor is reduced (i.e., 0.4 (kg/s)/ $\text{m}^{5/2}$ for a vent factor of 5 $\text{m}^{5/2}$).

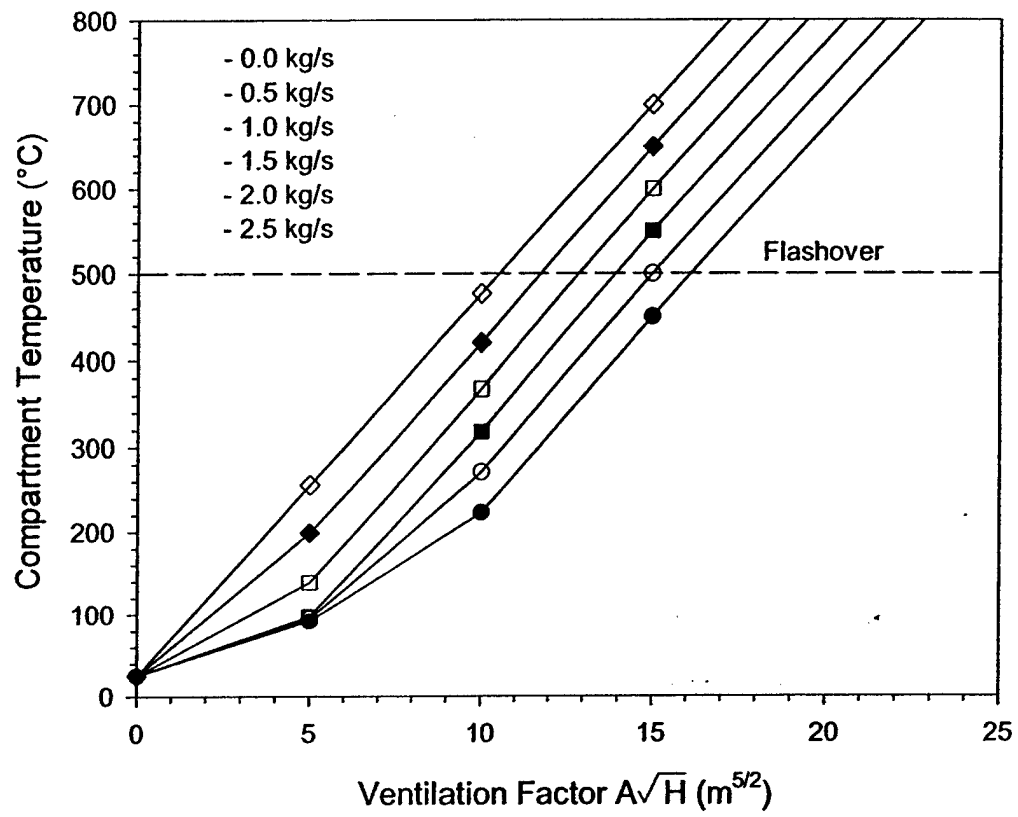


Figure 2 – Two-layer Temperature Predictions

4.2.4.2 One-layer (well-stirred) Analysis

In the well-stirred analysis, the equations in Section 4.1 were solved simultaneously until the oxygen concentration predicted by Equation (12) equaled 13 percent by volume. This is equivalent to selecting a combustion efficiency of 38 percent for Equation (2) ($C = 0.38$). The well-stirred analysis was conducted for the same range of the mist discharge rates and ventilation factors. The steady-state temperatures predicted in the PDA as a function of water mist discharge rate and vent factor are shown in Figure 3. The amount (percentage) of water/mist evaporated in each scenario is shown in Figure 4.

As shown in these two figures, the thermal management capabilities of the system are significantly reduced when a majority of the water/mist discharged by the system is being evaporated. Once all of the water being discharged is evaporated, the thermal conditions would rapidly approach the two-layer predictions. Systems that discharge more than this critical value are all capable of maintaining the temperatures in the PDA below 70°C (158°F).

Once the critical mist discharge rate is exceeded, increasing the flow has only a minimal effect on the compartment temperatures. The explanation for these similar temperatures is associated with the amount of water being evaporated. The primary energy absorption mechanism is the evaporation of water, which increases until the gases flowing through the compartment are saturated with water vapor. Once the mist discharge rate is adequate to produce saturation, the addition of more water only slightly reduces the temperatures in the space.

The amount/percent of the water discharged by the system that is evaporated in the thermal management process is also related to the well-stirred assumption. In the absence of actual test data, a conservative approach would be to assume that once one-half of the water discharged by the system/nozzles is being evaporated, the well-stirred conditions begin to deteriorate, and the temperatures in the space begin to approach those predicted in the two-layer analysis. This equates to a critical mist discharge rate of $0.10 \text{ (kg/s)/m}^{5/2}$. It should be noted that this relationship is not perfectly linear and that the critical value of $0.10 \text{ (kg/s)/m}^{5/2}$ applies to the larger ventilation factors. The critical value for the smaller vent factors can be slightly reduced as the ventilation factor is reduced (i.e., $0.07 \text{ (kg/s)/m}^{5/2}$ for a vent factor of $5 \text{ m}^{5/2}$).

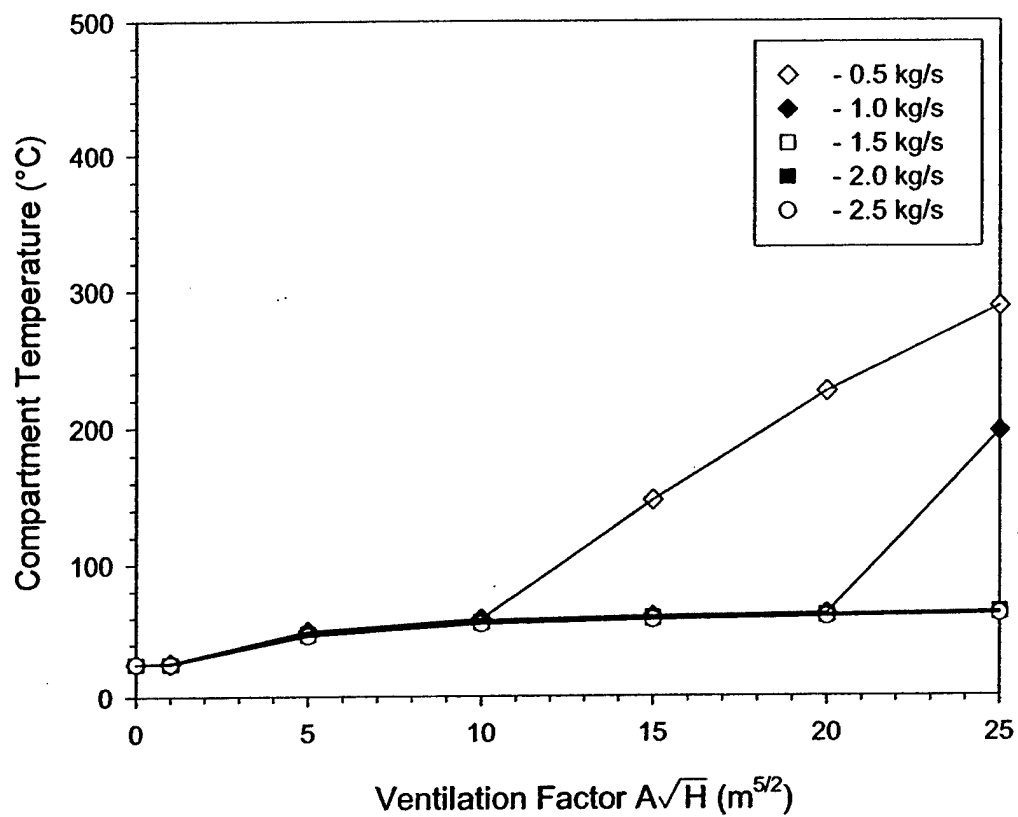


Figure 3 – One-layer (well-stirred) Thermal Predictions

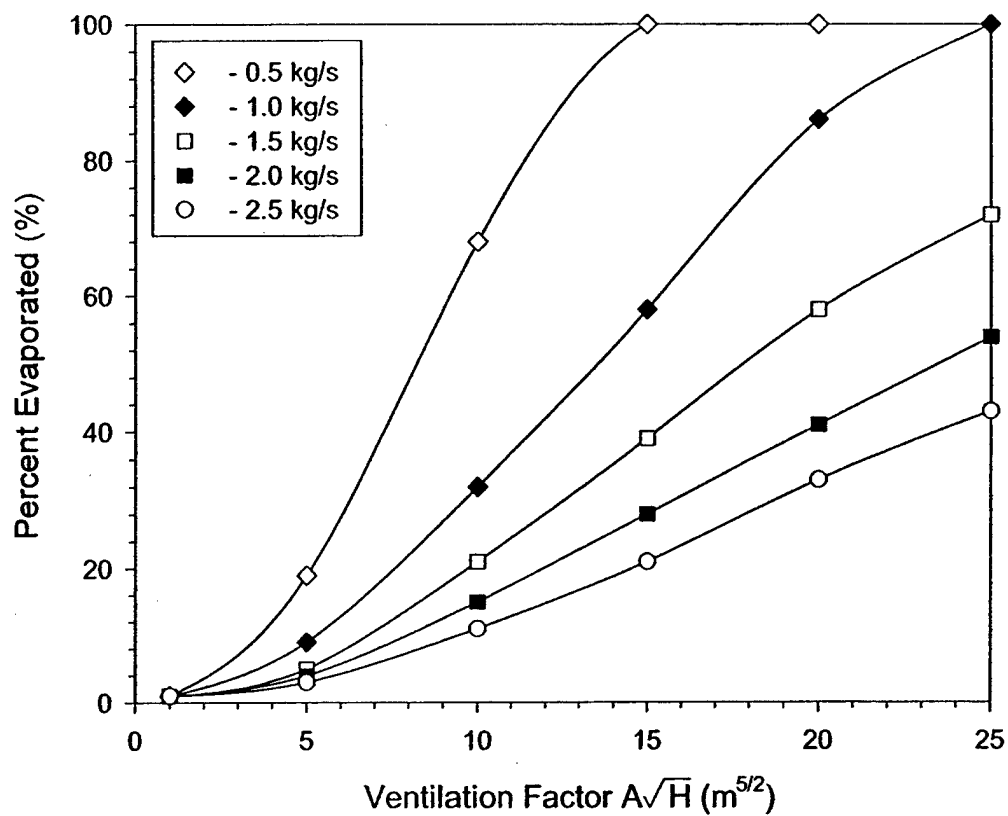


Figure 4 – One-layer (well-stirred) Evaporation Rates

4.2.4.3 Analytical Summary

The two approaches (two-layer and one-layer (well-stirred)) tend to bound the potential conditions in the PDA following a weapon hit. When considering/developing water mist system design parameters/ characteristics, emphasis should be placed on achieving well-stirred conditions in an attempt to thermally manage the temperatures in the space with the least amount of water. By producing well-stirred conditions, the heat release rate of the fire is significantly reduced by exposing the fire/fuel to water vapor and vitiated gases. These benefits are shown for a range of battle damage conditions (three size openings to the weather) in Figures 5, 6 and 7.

Figure 5 illustrates the bounding conditions in the PDA as a function of mist discharge rate for a smaller opening to the weather (ventilation factor of $5 \text{ m}^{5/2}$ (1.8 m x 1.8 m (6 ft x 6 ft))). Figure 6 illustrates these conditions for a medium size opening (ventilation factor of $10 \text{ m}^{5/2}$ (2.5 m x 2.5 m (8ft x 8 ft))), and Figure 7 illustrates the conditions for a larger opening (ventilation factor of $15 \text{ m}^{5/2}$ (3 m x 3 m (10 ft x 10 ft))).

As shown in Figure 5, due to the small size of the opening (limiting the oxygen available to support combustion), the unabated fire would only reach 7.5 MW and produce upper layer temperatures on the order of 200 °C. Although the conditions in the PDA are not severe with respect to the global environment, depending on the type and configuration of the fuel in the space, localized heating of bulkheads and decks could still result in fire spread to adjacent spaces. In this scenario, only a minimal amount of water mist would be required to mitigate the hazard and significantly reduce the likelihood of fire spread.

As shown Figures 6 and 7, both of the larger vent openings could support flashover conditions (upper layer temperatures in excess of 500 °C) if the fire burned unabated. In either situation, if the mist system was capable of uniformly mixing the gases in the PDA, less than 1.0 kg/s (16 gpm) of water would be needed to reduce the average temperature in the space below 75 °C (167 °F). A majority of this temperature reduction is associated with the suppression of the fire (reduction in heat release rate due to the lower oxygen concentration at the fire) rather than the absorption of heat. In both cases, the fire size was reduced by an order of magnitude due to the discharge of the mist. If the mist system cannot produce a well-stirred environment (i.e., a two-layer system), significantly more water is required to reduce the temperatures in the PDA to less than 100 °C. In either case, the required flow rates are fairly low when considering the volume/area of the PDA. A water mist system designed to meet the DC-ARM requirements would discharge approximately 760 Lpm (200 gpm) of mist in the area of the ship designated as the PDA. This is approximately an order of magnitude greater than that required to thermally manage the conditions in the space.

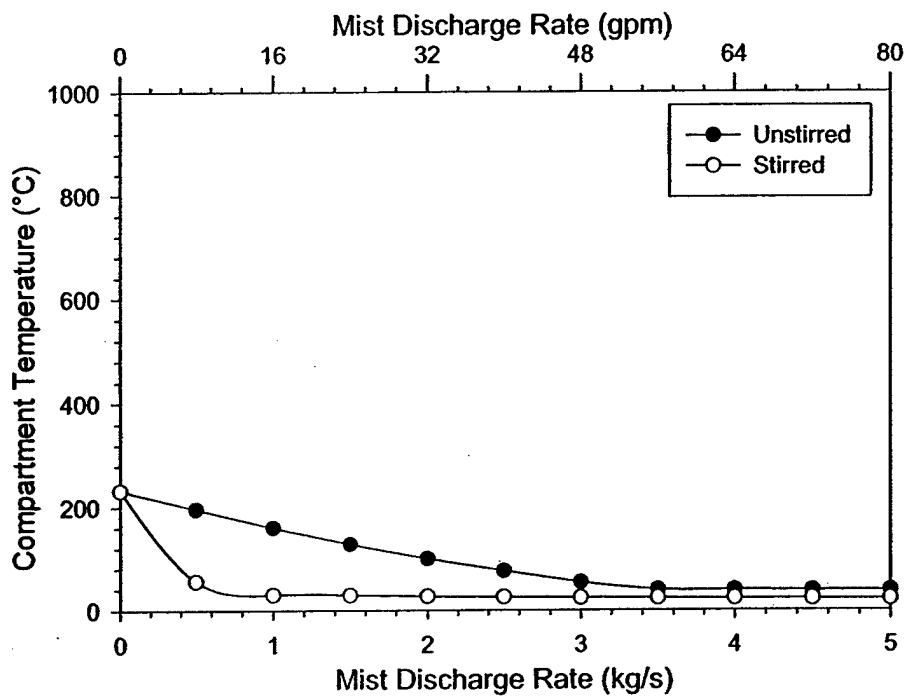
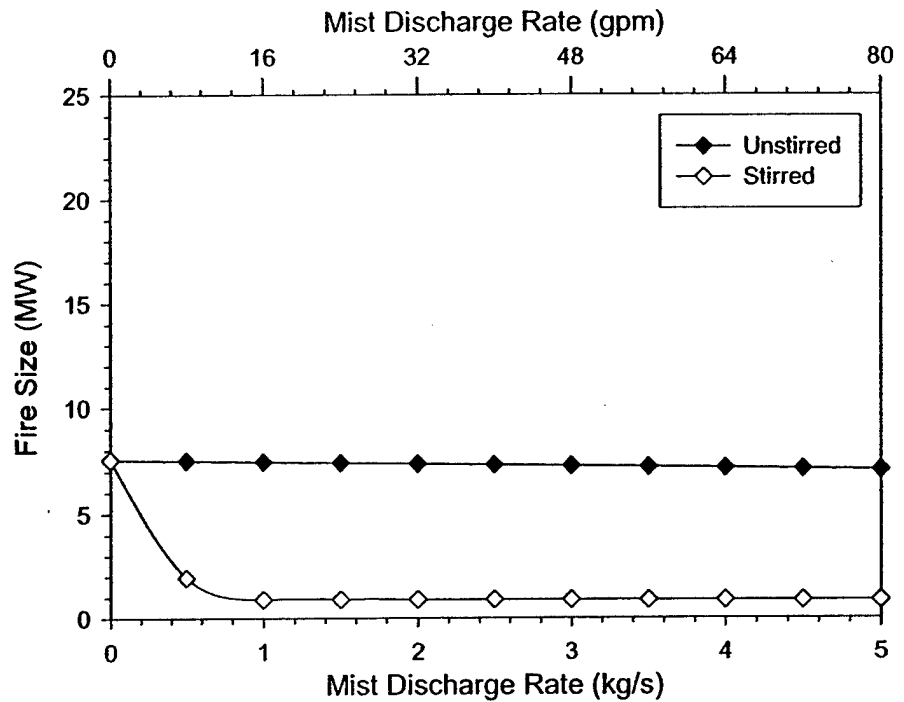


Figure 5 – Bounding Conditions
(Compartment: 30 m x 10 m x 5 m/Vent Factor - 5 m^{5/2})

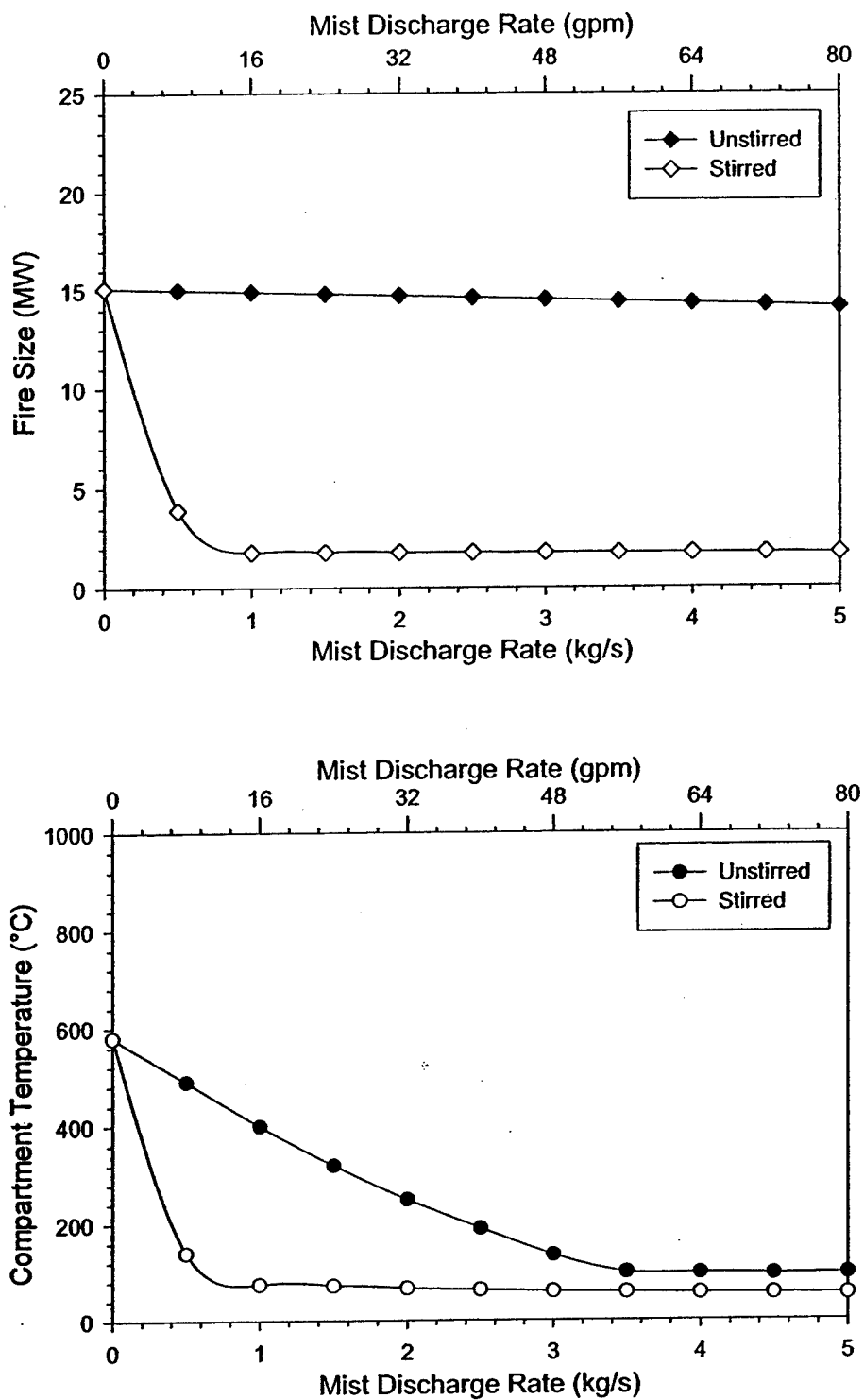


Figure 6— Bounding Conditions
(Compartment – 30 m x 10 m x 5 m/Vent Factor – 10 m^{5/2})

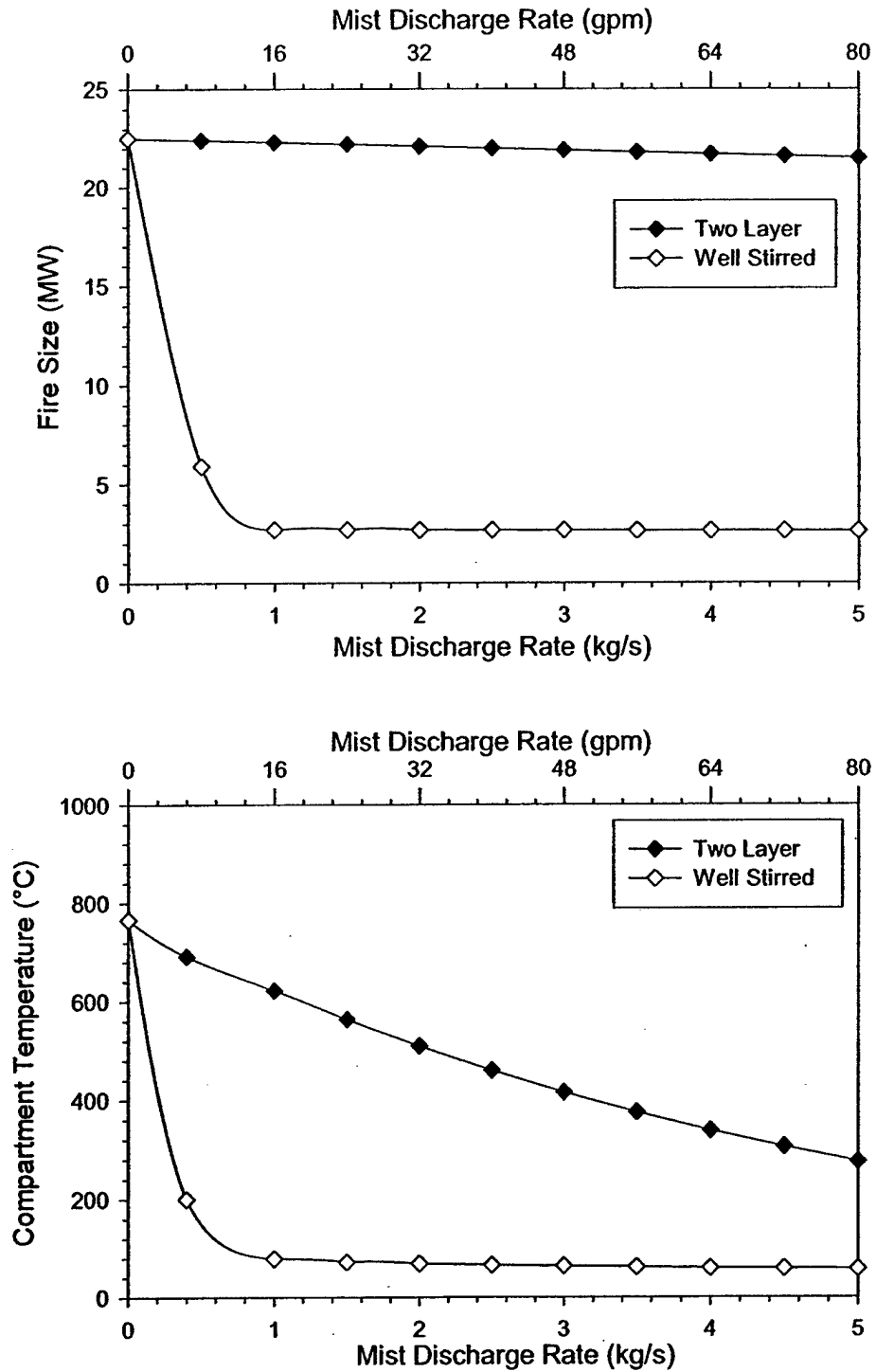


Figure 7 – Bounding Conditions
(Compartment – 30 m x 10 m x 5 m/Vent Factor – 15 m^{5/2})

5.0 WATER MIST SYSTEM DESIGN CONSIDERATION

There is a significant body of data that demonstrates that uniformly spaced overhead mist nozzles can produce well-stirred conditions in almost any compartment configuration [18]. However, previous weapon effects testing has shown that systems running through the PDA, particularly in the overhead near the centerline of the ship, are most susceptible to damage and are unlikely to survive the blast. As a result, new design approaches need to be developed and tested to determine their survivability and their capabilities to mix the gases in the PDA (i.e., produce well-stirred conditions).

The simplest design approach to increase system survivability would incorporate sidewall nozzles installed in each bulkhead. (Depending on the ship configuration, nozzles may be required on the athwart-ship bulkheads.) In order for this design to produce the desired well-stirred conditions, the system must discharge mist with a high enough momentum to reach halfway across the PDA (in this exercise, 4.6 m (50 ft)). Only a limited number of high pressure water mist systems have adequate momentum to meet this objective. The nozzle spacing/location in such a design is also critical. Other types of water mist systems, such as low and intermediate pressure single fluid systems or twin fluid systems, are unlikely to produce these conditions [19].

If it is determined that the clutter/obstructions in the space is likely to prevent even an optimized system from producing well-stirred conditions, the system may still provide significant advantages. At minimum, the system should be capable of thermally managing the conditions/gas temperatures in the area local to the nozzles. This would provide two functions: prevent fire spread horizontally outside the PDA, and prevent ignition of combustibles near the boundary. Since previous WET evaluations noted that a significant portion of the contents (combustibles) in the space are blown/thrown against the closest intact boundary, pre-wetting the material located near these boundaries may also significantly reduce the duration of the fire.

In some scenarios, thermally managing the conditions at the perimeter of the PDA may, in itself, be adequate to prevent fire spread in all directions (both horizontally and vertically). In a significant number of the cases (actual data and predictions), the point of detonation is located almost exactly in the center of the PDA. This center location is least likely to be well-stirred due to the distance from the nearest water mist nozzles. However, due to the holing in the decks and the relocation of combustibles away from this area, the amount of fuel at this location would be limited. This lack of fuel may prevent localized plume effects from spreading fire vertically upward in this region while the thermal management provided by the mist around the perimeter prevents fire spread to the adjacent spaces.

6.0 SUMMARY

A water mist system that incorporates a survivable design has the potential to significantly reduce the thermal conditions in the PDA following a weapon hit. This reduction in thermal conditions would certainly prevent flashover and could potentially prevent fire spread to adjacent compartments.

The analysis put forth in this paper demonstrates that the likelihood of the PDA to reach flashover following a weapon hit is a function of the size of the opening to the weather created by the blast. Up to the point where the fire becomes fuel surface limited, the larger the vent opening, the greater the fire size and the higher the resulting compartment temperatures. The increased air flow provided by the larger vent opening also dictates the amount of water vapor required to saturate the gases in the PDA. As a result, the amount of mist required to achieve thermal management is also a function of the size of the vent opening. A review of previous weapon effects tests, ship vulnerability modeling predictions, and incident data suggests that large vent openings are, however, less likely.

The results of this analysis demonstrate that the conditions produced by the fire following a typical weapon hit could be mitigated (i.e., thermal management of the conditions in the PDA and the prevention of fire spread to adjacent spaces) by appropriately discharging a minimal amount of water mist into the PDA. Separate R&D programs have been proposed to study the effects of preemptive discharge of water mist on mitigating the effects of the blast. The results show that 40-80 Lpm (10-20 gpm) of water mist could potentially cool the PDA to less than 100°C and prevent fire spread to adjacent spaces for the range of battle damage conditions included in this analysis.

Additional research is needed to bound/confirm some of the assumptions adopted during this analysis. More specifically, the ability of sidewall nozzles or other potentially survivable designs to produce well-stirred conditions in the PDA needs to be evaluated for a range of mist system, compartment geometries, and ventilation parameters. This research is tentatively scheduled for the Spring of FY02.

7.0 REFERENCES

1. Williams, F.W., Tatem, P.A., Nguyen, X., Durkin, A., Parker, A.J., Strehlen, B.D., Scheffey, J.L., Pham, H., Wong, J.T., Darwin, R.L., Runnerstrom, E., Lestina, T., Downs, R., Bradley, M., Toomey, T.A., and Farley, J.P., "Results of 1998 DC-ARM/ISFE Demonstration Tests," NRL/FR/6180-00-9929, 25 April 2000.

2. Peatross, M.J., Luers, A.C., Pham, H.V., Scheffey, J.L., Wong, J.T., Downs, R. Runnerstrom E., Williams, F.W., Farley, J.P., Tatem, P.A., Durkin A. and Nguyen, A., "DC-ARM Final Demonstration, Report" NRL 6180/0029, 13 January 2001.
3. Luers, A.C., Gottuk, D.T., Pham, H.V., Scheffey, J.L., Wong, J.T., Farley, J.P., Williams, F.W., Tatem, P.A., and Nguyen, X., "FY 2001 DC-ARM Demonstration Final Report," NRL/FR/6180-03-10,056, June 23, 2003..
4. International Maritime Organization, "FTP Code, International Code for Application of Fire Test Procedures," London, England, 1998.
5. Back, G.G. Williams, F.W., DiNenno, P.J., Farley, J.P., Hill, S.A. Darwin, R.L., Toomey, T.A., and Havlovick, B.J., "Full-Scale Machinery Space Water Mist Tests: Full Design Validation," NRL/Memo Report/6180-99-8380, 12 June 1999.
6. Mawhinney, J.R., DiNenno, P.J., and Williams, F.W., "New Concepts for Design of an Automated Hydraulic Piping Network for a Water Mist Fire Suppression System on Navy Ships," NRL Ltr Rpt Ser 6180/0292, July 18, 2000.
7. Back, G.G., Mawhinney, J.R., Peatross, M.J., Scheffey, J.L., and Williams, F.W., "DC-ARM Water Mist System Operational Modes: Development and Validation (Test Plan)," NRL Ltr Rpt Ser 6180/0125, 16 March 2001.
8. Babrauskas, V., and Williamson, R.B., "Post Flashover Compartment Fires: Application of a Theoretical Model," *Fire and Materials*, 3, 1979.
9. Department of the Navy, "Naval Ships Technical Manual Chapter 555-Volume 1, Surface Ship Fire Fighting," S9086-S3-STM-010/CH-555V1, Washington, DC, 2 December 1996.
10. Drysdale, D., *An Introduction to Fire Dynamics*, Chapters 2 and 10, John Wiley and Sons, New York, NY, 1985.
11. Office of Naval Research, FNC Executive Plan, "Advanced Damage Countermeasures (ADC)," 11 March 2002.

12. Peatross, M.J., Beyler, C.L., and Back, G.G., "Validation of Full Room Involvement Time Correlation Applicable to Steel Ship Compartments," Rpt CG-D-16-94, U.S. Coast Guard R&D Center, Groton, CT, November 1993.
13. Keenan, J.H., Keyes, F.G., Hill, P.G., and Moore, J.G., *Steam Tables*, Wiley, New York, 1969.
14. Wolk, H., "Ship Vulnerability Model (Version 12) NSWC/CD POC."
15. Back, G.G., Iqbal, N., Williams, F.W., and Scheffey, J.L., "Potential Compartment Fire Growth Curved Resulting from a Missile Hit," NRL Ltr Rpt Ser 6180/0526, 27 October 1998.
16. Peacock, R.D., Forney, G.F., Reneke, P., and Jones, W.W., "CFAST, the Consolidated Model of Fire Growth and Smoke Transport (Version 2.0.1)," NIST Technical Note 1299, National Institute of Standards and Technology, Gaithersburg, MD, January 2000.
17. Beyler, C.L., "Flammability Limits of Premixed and Diffusion Flames," Chapter 2-7, *The SFPE Handbook of Fire Protection Engineering*, 3rd Edition, National Fire Protection Association, Quincy, MA, 2002.
18. Back, G.G., Beyler, C.L., and Hansen, R., "The Capabilities and Limitations of Total Flooding Water Mist Fire Suppression Systems in Machinery Space Applications," *Fire Technology*, **36**, February 2000.
19. Mawhinney, J.R., DiNenno, P.J., and Williams, F.W., "Water Mist Flashover Suppression and Boundary Cooling System for Integration with DC-ARM: Volume I: Summary of Testing," NRL/MR/6180-99-8400, September 30, 1999.